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Effects of Diagenesis on the Reservoir Quality in the Upper Sands of Lower Goru Formation, Badin Block, Lower Indus Basin, Pakistan

Humaira Dars[1], Muhammad Hassan Agheem[1]*, Sarfraz Hussain Solangi[1], Akhtar Hussain Markhand[1], Ali Ghulam Sahito[1], Qamaruddin Khokhar[1], Ghulam Mustafa Thebo[1], Shahid Ali Shaikh[1]

Centre For Pure and Applied Geology, University of Sindh, Jamshoro, Pakistan

*Email: mhagheem@usindh.edu.pk

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Abstract: The core samples of B member of upper sand reservoir rocks of the lower Goru Formation from three wells of the Badin block were studied using thin section, XRD, and SEM techniques to investigate the diagenetic trends and their effect on reservoir quality. Microscopic study indicates that the B sand unit is mature with quartz as the predominant mineral constituent with variable amount of feldspar and lithic minerals. The QFL plot indicates that most of the samples are plotted in the field of quartz arenite, sub-litharenite and sub-arkose respectively. A few samples belong to the category of litharenite and feldspathic litharenite. The feldspars were partially to completely altered to kaolinite and other clay minerals. Coarse-crystalline or micro-crystalline calcite is the predominant cementing material. Bulk rock XRD analysis also confirms that the main mineral constituents of there samples are quartz and calcite in variable proportions. The undulose extinction and fracturing of quartz grains indicate that the area remained under stress. Moreover, such fracturing is post-depositional and therefore is the product of late diagenesis. Scanning Electron Microscopic (SEM) images at 50 micrometer (μm) size show irregular type of fracturing within the quartz grains. This late stage fracturing of quartz has also generated various types of channels which may serve as secondary porosity. The quartz overgrowth was observed in some samples due to late stage diagenesis. The micro-crystalline cement in the form of calcite is mostly present within the pores in fractured quartz. The results indicate that the diagenesis played a significant role in improving the reservoir characteristics of B sand by increasing the porosity due to quartz fracturing, feldspar dissolution, alteration and quartz corrosion. Hence, better understanding of reservoir heterogeneities in porosity through diagenetic studies can be helpful in evaluating potential reservoir horizons for hydrocarbon accumulation on spatial and temporal scales.

Keywords: Lower Goru, diagenesis, reservoir quality, Badin block, lower Indus basin.

Introduction

The sandstone units of the Goru Formation, particularly of the lower Goru have been of much interest for the petroleum exploration and production companies for many decades, but published literature was still lacking. The available studies are more descriptive and deal with lithology, lithofacies distribution, sequence stratigraphy and petrophysics (Kadri, 1995; Ebdon et al., 2004; Sahito et al., 2013; Solangi et al., 2016). Some studies have also been done to understand the diagenetic controls on the variation of porosity and permeability within the most producing and promising reservoir sands of lower Goru Formation (Mohsin et al., 2010; Baig et al., 2016; Sadaf et al., 2018). However, considerable potential remains untapped because of partial understanding of the distribution of reservoir, key reservoir facies, diagenesis and its effects on reservoir quality. The diagenetic episodes are generally responsible for generation, retention and destruction of porosity (Bjørlykke et al., 2004; Boles and Franks, 1979; Hawkins, 1987; Medina, 2011). The sandstones of lower Goru Formation are proven hydrocarbon reservoirs in the lower Indus basin and many oil fields are producing oil and gas for many decades. The Khaskheli oil field is the first and largest oil field in Pakistan situated in the south eastern part of lower Indus basin in Badin area (Kadri, 1995). In lower Indus basin, > 12TCF gas reserves and over 100 million barrels oil have been discovered and almost 90% of oil production is from Badin area. While, 60% reserves and production are only from the early Cretaceous lower Goru sandstone (Jamil et al., 2012). The informally named B Sand (a part of the upper Sand, lower Goru Formation) is the most important reservoir unit. Lithologically, the lower Goru is predominantly a marine and marginal marine shale and silt. There are a number of sandstone horizons within shales and silts (Sahito et al., 2013; Solangi et al., 2016). The spatial and temporal changes in permeability and porosity in lower Goru sandstone horizon is a common phenomenon and has resulted in numerous setbacks because the sandstone at many places has been found unexpectedly compact. It is most probably due to spatial and temporal variation in diagenesis of sandstone horizons. After the discovery of Khaskheli oil field in 1981, the Badin block remained the focus for exploration of hydrocarbon by different national and multi-national companies. Since then several studies have been carried out covering different aspects (Kadri, 1995; Ebdon et al., 2004; Sahito et al., 2013; Solangi et al., 2016). Diagenesis has a significant role in the characterization of any reservoir rock. It is a process which may enhance or reduce the porosity as well as the permeability of a rock that plays a vital role

Table 1. Depths of B-Sand samples of lower Goru Formation for Well No. A, B and D.

Well-A		Well-B		Well-D	
Sample No.	Depth in Feet	Sample No.	Depth in Feet	Sample No.	Depth in Feet
A1	6094.5	B1	2521	D1	5873
A2	6097	B2	2522	D2	5874
A3	6099.4	B3	2524	D3	5878.6
A4	6104.3	B4	2526	D4	5881
A5	6107	B5	2527	D5A	5885
A6	6109	B5(b)	2529	D5B	5885.5
A7	6112	B6	2530	D6	5889
A8	6114.8	B7	2532	D7	5891.7
A9	6119	B8	2534	D8	5893.5
A10	6120.9	B9	2536	D9	5897
A11	6123.7	B10	2538	D10	5898
A12	6126.5	B11	2539	D11	5898.8
A13	6128	B12(a)	2541	D12	5900.4
A13-B	6131.4	B12(b)	2541.8		
A14	6140	B13	2543		
A15	6143	B14	2544		
A16	6145	B15	2546		
A17	6148.6	B16	2549		

in the evaluation of any reservoir rock (Metarko, 1980; Bjørlykke et al., 1986; Walderhaug, 1994; Medina et al., 2011). Keeping in view the significance of diagenesis in the characterization and evaluation of reservoir rock, three wells of Badin block (i.e., well A, well B and well D) were chosen for the present study (Table 1).

Materials and Methods

Core samples from three wells of B-Sands of lower Goru Formation were obtained from the British Petroleum (BP). Twenty-eight out of total 52 samples were selected keeping in view the depth and variation in lithological characteristics. The thin sections of the selected core samples were prepared for petrographic studies using polarizing microscope (Leica, DM2500). To support the petrographic studies, X-ray Diffraction analyses were carried out using D-8 Advance X-Ray diffractometer. To figure out the size, shape and morphology of the grains at micrometer level, the Scanning Electron Microscope (SEM) was used. In addition, Energy Dispersive Spectrometer (EDS) was used to determine the mineral chemistry and identification of main mineral constituents, types of cement and diagenetic products.

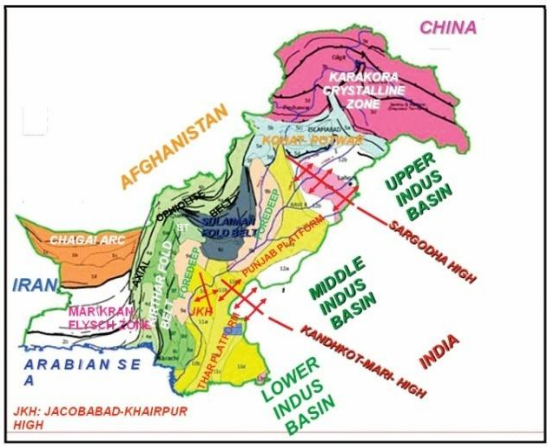

Fig. 1 Tectonic framework of Pakistan and Indus basin divison.

Geology and Tectonics of the area

Lower Indus basin is a well-known producing basin for hydrocarbon exploration. It is located in the southern part of Pakistan (Fig. 1). The Khaskheli oil field at Badin block was breakthrough discovery in lower Indus basin (Kadri, 1995). The lower Goru sands have been important hydrocarbon producers during the last two decades. Moreover, considerable potential remains untapped because of gaps in understanding factors affecting the fundamental reservoir characteristics such as porosity and permeability.

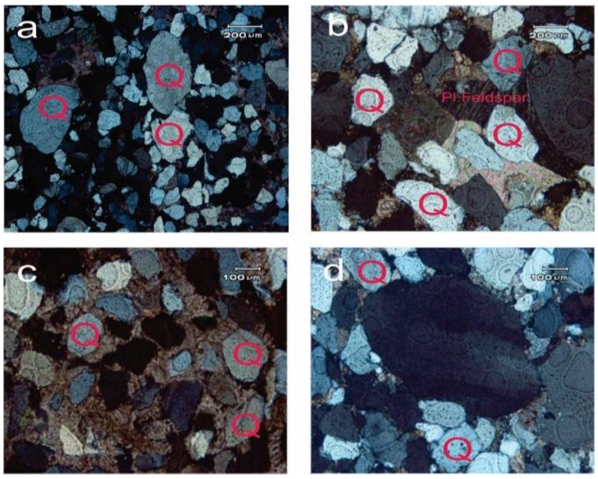

Fig. 2 (A) Poorly sorted, angular to sub-rounded quartz grains. Microcrystalline calcite cement is present in lower right side and coarse-crystalline calcite in upper left side; (B) Plagioclase feldspar along muscovite; (C) Grains are floating in the microcrystalline calcite cement; (D) Quartz grain in the centre with undulose extinction.

At the end of Jurassic, Indian plate started rifting and drifting away from the super continent Pangea towards north and collided with the Eurasian plate in Paleogene time. Northward movement of Indian plate created compressional forces while associated anticlockwise rotation resulted in tensional forces (Waples and Hegarty, 1999). Due to such tension, the platform was divided into horsts and grabens which formed Kutch and Cambay rift basins. Such rifting, extensional faulting and shearing had taken place in the southern Indus basin in the form of Badin rift basin (Wandreyetal., 2004). The favorable tectonic framework allowed the extensive deposition of sediments in the form of different facies including organic rich Sembar shale and porous-permeable lower Goru sands (Raza et al.,1990). Afterwards, a transgressive event took place in the form of upper Goru which works as a regional seal to lower Goru reservoir units.

Overview of Lower Goru Formation

The lower Goru Formation predominantly comprises of marine or marginal marine shales, sandstones, silt and mudstones (Williams, 1959). There are a number of sandstone horizons within shale and silt units. Oil and gas accumulations occur in these sandstone horizons within the lower Goru Formation. From top to bottom these are informally termed as the upper, middle and basal sands of Aptian-Albian age. Of these reservoirs, the upper sand comprises of four different sandstone horizons i.e. A, B, C, and D in descending order which are separated by shale layers. Upper sands are economically most important as more than 100 hydrocarbon discoveries have been made in either A or B sands (Solangi et al., 2016). The B sand unit is the most productive and bounded by Badin shale at bottom and Turk shale at top. Lower Goru Formation has been extensively studied from different aspects of petroleum geology, diagenetic history, trends and their effects on the quality of reservoir and hydrocarbon production (e.g., Ebdon et al., 2004; Mohsin et al., 2010; Sahito et al., 2013; Solangi et al., 2016; Baig et al., 2016; Sadaf et al., 2018).

Results and Discussion

Petrographic and Diagenetic Study

Petrographic studies of three selected wells indicate that the B-sands are fine to medium grained and medium to coarse grained sandstones. Different authigenic minerals include quartz, feldspar, calcite, dolomite, kaolinite and iron oxide. Calcite, quartz and kaolinite are the major cement types.

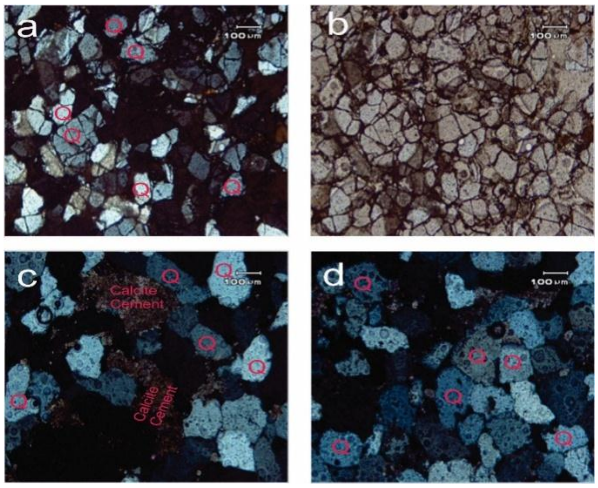

Fig. 3 (Mag: 100X for A, B, and 40X for C, D): (A, B) Intensive fracturing within the quartz grains; (C) Microcrystalline cement replacing quartz margins; (D) suture grain contacts showing compaction and dissolution.

Extreme mechanical and chemical compaction due to uninterrupted burial is observed which resulted in loss of primary porosity. The compaction was so intense that it made the grains to penetrate into one another due to increased overburden and pressure. The effects of compaction are also obvious from straight, concavo-convex as well as sutured contacts of adjoining framework grains (Fig. 3). First sandstones were subjected to mechanical compaction up to the beginning of calcite cementation and the process of mechanical compaction ceased due to enormous calcite cementation.

These samples are largely composed of mono crystalline quartz and the polycrystalline quartz is up to 3% and shows significant quartz overgrowth (Fig. 5). Most of the quartz grains are unstrained but undulose extinction is common, showing deformation which is late diagenetic process (Fig. 2). Another late diagenetic effect in the form of quartz overgrowth and

Table 2. Framework composition of B-Sands of Well No. A, B, and D.

Sample No.	Framework composition			Folk Classification (1974)
	Quartz	Feldspar	Lithics	
A-2	88.60	5.06	6.30	Sublitharenite
A-5	97.80	2.19	0.00	Quartz Arenite
A-9	62.29	8.90	29.58	Feldspathic Litharenite
A-11	84.00	4.00	11.25	Litharenite
A-17	100	0.00	0.00	Quartzarenite
B-1	70.00	8.70	21.00	Feldspathic litharenite
B-5	85.00	5.60	9.00	Sublitharenite
B-8	74.11	4.70	21.17	Litharenite
B-10	41.66	16.60	41.66	Litharenite
B-16	25.00	0.00	0.00	Shale
D-1	75.34	0.00	24.65	Sublitharenite
D-4	82.85	14.20	2.80	Subarkose
D-6	86.83	5.70	7.20	Subllitharenite
D-8	96.15	0.00	3.84	Quartzarenite
D-12	97.40	2.50	0.00	Quartzarenite

fracturing was observed. Planar and sutured grain contacts are observed between the quartz grains showing compaction and dissolution. In some samples which are generally fine to coarse grained and cement supported, the sandstones have point to floating grain contacts (Fig. 4, 6).

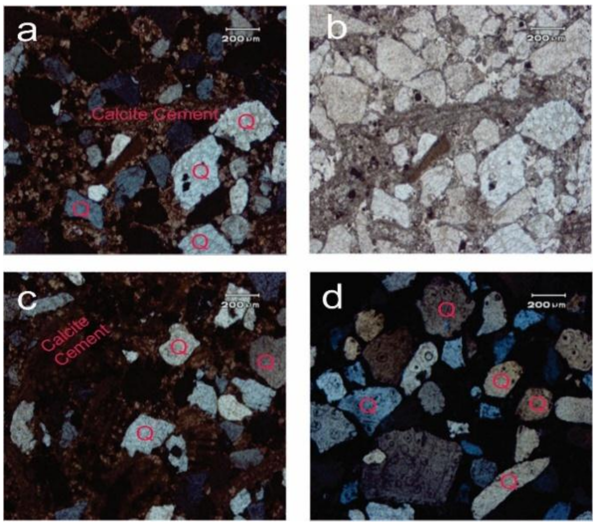

Fig. 4 (Mag: 40X): (A, B, C) Poorly sorted, angular to sub-angular grains with floating texture and point contacts. Bioclasts are present in the central part; one is totally replaced by calcite; D) moderately packed, sub-spherical to spherical and prismoidal grains are present with point and long contacts.

In fine to medium grained sandstones, point contacts are common, while at places concavo-convex grain contacts are seen. The SEM images at 50 micrometer size show irregular type of fracturing within the quartz grains (Fig. 8, 9). This late stage fracturing of quartz has also generated various types of channels resulting in secondary porosity in the basal sand of lower Goru (Mohsin et al., 2010; Sadaf et al., 2018).

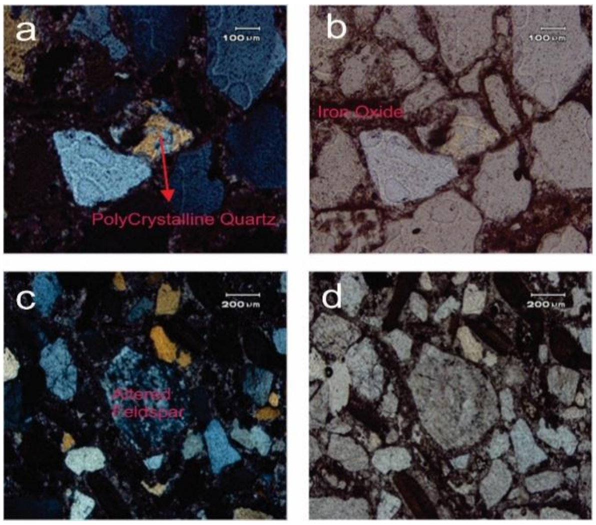

Fig. 5 (Mag: 100X): Polycrystalline quartz in the centre of photomicrograph. Microcrystalline calcite is developed along the grain contacts of quartz (A, B); angular, quartz poor, calcite rich, have floating texture. In the centre a grain of alkali feldspar is partially altered to clays probably into kaolinite, illite/smectite. The bioclasts in the form of lithics are scattered throughout of the slides (C, D).

At places, the sides of quartz grains are corroded due to replacement by calcite cement. Generally, authigenic quartz forms overgrowths on detrital grains, where its surface is covered by kaolinite. Authigenic quartz is normally formed on clean and clay free parts of the detrital grain surfaces that tends to grow outward and laterally to form quartz overgrowth. However, if clay was present, it obstructed the complete quartz overgrowth and resulted in irregular quartz cementation. Formation of early calcite matrix (microcrystalline) reduced the primary porosity (Fig. 2, 4) and retarded quartz cementation. The amount of quartz overgrowth may be overlooked because of its small size and un-recognizable boundaries between some overgrowths. Moreover, quartz overgrowths are common in all three wells, laterally as well as vertically.

Fig. 6 (Mag: 40X): Poorly sorted, angular to sub angular quartz grains having floating contacts. The microcrystalline calcite is clearly visible (A, B); various bioclasts embedded within the angular to sub-angular quartz grains (C, D).

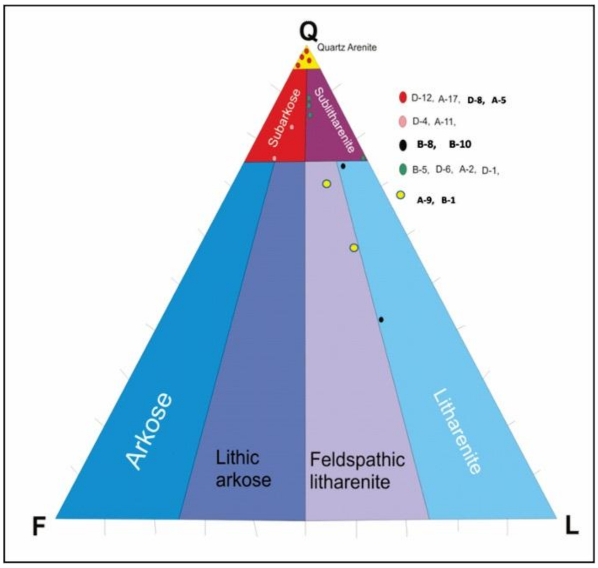

Fig. 7 Classification of B-Sands of Lower Goru according to Folk (1974) Classification.

Table 3. Modal Mineral Composition of B-Sands of Well No. A, B, and D.

Minerals	Samples		A-2	A-5	A-9	A-11	A-17	B-1	B-5	B-8	B-10	B-16	D-1	D-4	D-6	D-8	D-12
Quartz	Qm		70	88	38	84	86	38	72	62	28	25	53	57	60	50	74
	Qp		-	-	-	-	-	3	3	1	2	-	2	1	-	-	1.9
Feldspar	AAF		4	2	5	4	-	5	5	4	12	-	-	10	3	-	2
	Plg		3	-	-	-	-	-	-	-	-	-	-	-	1	-	-
Cement	Cct		1	-	-	-	2	-	-	-	-	-	10	-	3	-	-
	Mct		15	4	35	7	6	34	10	15	20	-	15	9	21	-	14
Lithics	Ls	Bio	3	-	8	2	-	3	8	15	30	-	10	12	-	2	-
		Lmud	-	-	10	2	-	-	-	3	-	-	-	-	5	-	-
	Sd		4	-	-	-	-	8	-	-	-	-	8	-	-	-	-
Accessory Minerals	Tour		2	1	-	0.1	1	-	-	-	-	-	1	2	2	-	4
	Dol		2	-	4	-	-	-	2	-	-	-	-	-	4	-	-
	Biot		-	-	-	-	-	-	-	-	-	1	-	-	-	2	-
	Mus		Tr	-	-	-	-	1	-	-	-	5	1	-	-	-	-
	Chl		1	-	-	-	-	-	-	-	1	4	-	1	1	-	-
	Pyr		-	4	-	-	-	-	-	-	2	5	-	3	-	-	5
	Glt		-	1	-	1	5	-	-	-	-	-	-	-	-	-	0.1
	Ep		Tr	-	Tr	-	-	1	-	-	-	-	Tr	Tr	-	-	Tr

Calcite is common cement in the sandstone samples of all three wells and ranges from traces to 36% in thin sections (Fig. 2, 3, 5).

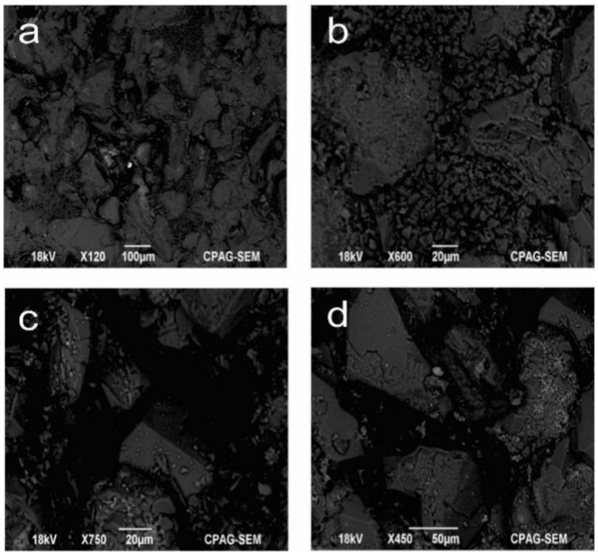

Fig. 8 Sample # A-4. Scanning Electron Microscope (SEM) images where the main constituent is quartz and its fracturing is very high as is evident in B, where the grain size is less than 10 µm. Secondary porosity and permeability is also visible along with the overgrowth of quartz itself (C, D).

Two generations of calcite cement have been identified i.e. coarse crystalline calcite and microcrystalline calcite. The percentage of microcrystalline calcite is higher than that of the coarse crystalline calcite (Fig. 2, 3). Coarse crystalline calcite ranges between 2-10%, whereas microcrystalline calcite ranges between 4-34% (Table 3).

Along with petrographic examination, the calcite is clearly identified in all samples by X-ray diffractogram (Figs. 15, 16). Calcite is present either in the form of intergranular cement or as crystalline or partial replacement of detrital components.

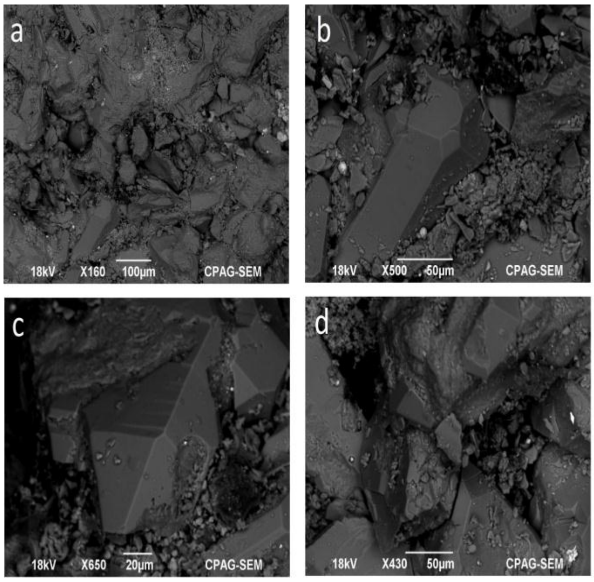

Fig. 9 SEM images of sample A-5. Quartz is the dominant phase with some euhedral crystals having both prismatic and pyramidal shapes. The cementing material is almost absent but compaction is there and, in the result, intensive fracturing has developed the channels for porosity and permeability. The overgrowth of quartz may also be seen (C, D).

Calcite replaced quartz and feldspar grains completely or partially along their margins. This cementation was so intense that it even penetrated into the grain pores, formed by dissolution of feldspar, which were filled later by authigenic calcite in a few sandstone samples. Sadaf et al. (2018) reported that quartz overgrowth is the major cementation phase of basal sands but the present petrographic, SEM-EDS and XRD results clearly show that calcite is the main cementation material of the B-sands along with the quartz overgrowth (Fig. 15).

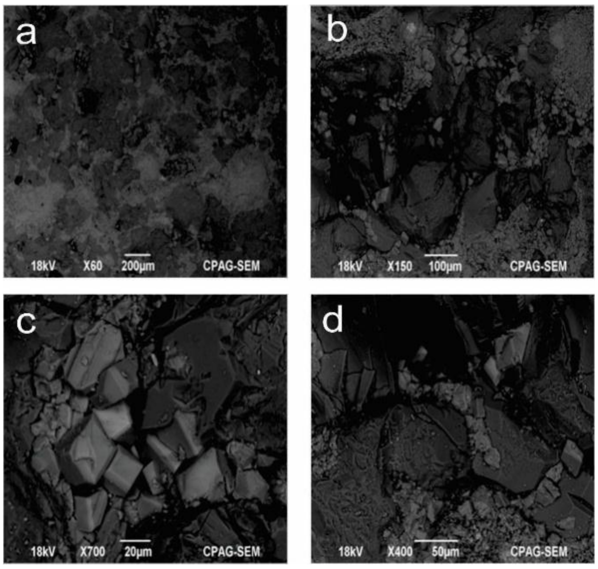

Fig. 10 SEM images of sample A-7. This sample is mainly composed of quartz but coarse-crystalline calcite of secondary generation is also the dominant phase with euhedral rhombus crystals of about 10-20 µm (A, C). Quartz corrosion and overgrowths are also visible (B, C, D). Along with quartz, the calcite is also fractured, showing that the fracturing is of two generations.

Though, calcite content is low in basal sands, but it is dominant in B-sands. However, in some samples, the percentage of calcite is higher or equal to quartz (Fig. 15).

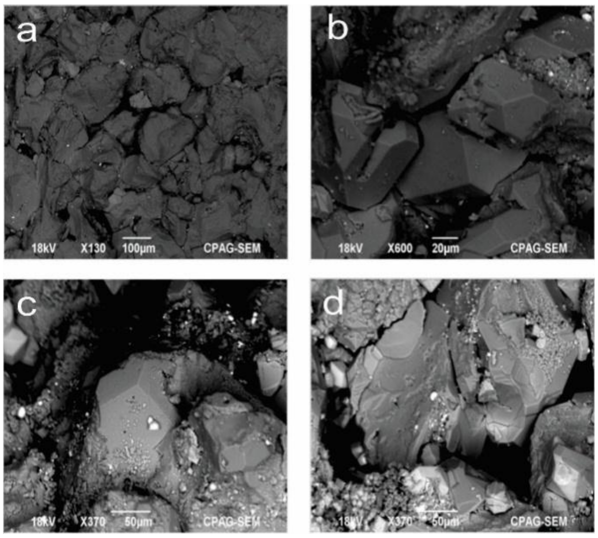

Fig. 11 SEM images of sample A-7 where quartz of typical conchoidal fracture is very clear. All of the four microphotographs are mainly composed of quartz. Like other samples, the intensive fracturing, corrosion and overgrowths of the quartz grains is visible.

Along with calcite, quartz is also present as a cementing material in these samples (Fig. 10A). There are diverse sources for the generation of secondary or authigenic quartz (McBride, 1989; Giles et al., 2000; Makowitz et al., 2006).

It is common that at the time of diagenesis, the sediments pass through different conditions that may create sources of SiO_2 for quartz cementation, such as dissolution of feldspar (Hawkins 1987), pressure solution (Houseknecht 1988; Dutton and Diggs, 1990; Bjørlykke and Egeberg 1993), alteration of clay minerals (Hower et al. 1976; Boles and Franks, 1979) and replacement of feldspar and quartz by calcite (Burley and Kantorowicz, 1986). In early diagenetic stages, the extensive dissolution of feldspar and kaolinization seem to be the possible sources of SiO_2 for quartz cementation (Duffin, 1989; Duffin et al., 1989).

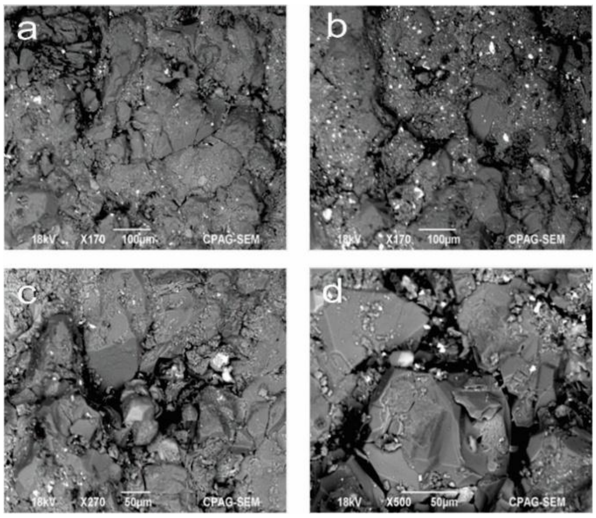

Fig. 12 SEM images of sample A-17. Conchoidal fracturing, corrosion and overgrowths of quartz grains are the dominant features. Black colored channels are showing the secondary porosity and permeability. White colored grains are giving more reflectance and may be the minute sulfide or other ore minerals.

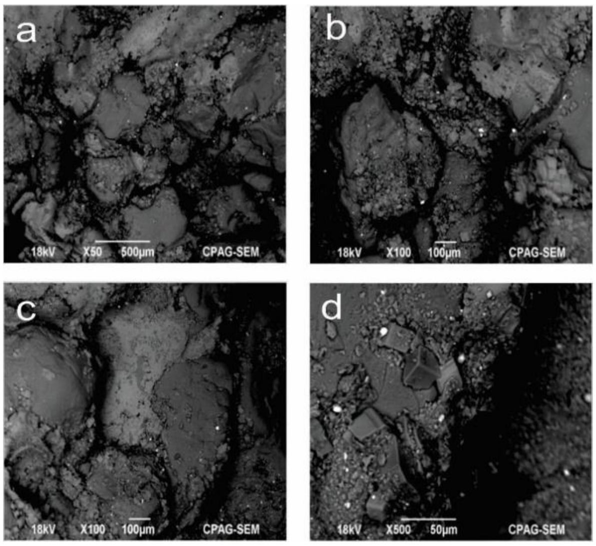

Fig. 13 SEM images of sample B-8. Two types of calcite along with quartz are present, which are mostly fractured and generated various kinds of channels ranging from 5-10 µm and generated secondary porosity and permeability.

In case of B sands of lower Goru, it is probable that the extensive dissolution of feldspar has generated the silica for quartz cementation. Minor dolomite rims are formed around altered volcanic fragments in few sandstone samples. X-ray diffractograms show a significant peak at 30.5 two-theta angle, which confirms the presence of dolomite (Fig. 15).

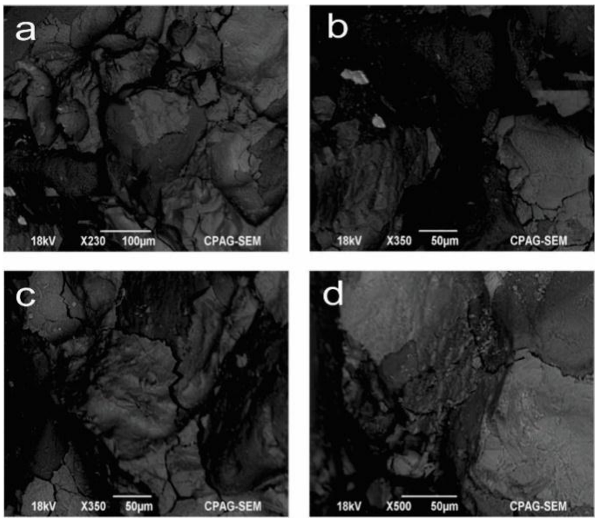

Fig. 14 SEM images of sample D-6. It is medium to coarse grained sandstone. Microcrystalline calcite cement is of early diagenesis. The secondary porosity and hence permeability in the form of connected channels is clearly visible.

Alkali feldspar has been noticed in thin section examination under polarizing microscope (Fig. 5C, D). The identified diagenetic clay is kaolinite and is present in most of the samples in minor amount. The feldspars are partially to completely altered into clay minerals such as kaolinite and illite and have reduced the primary porosity (Fig. 15, 16).

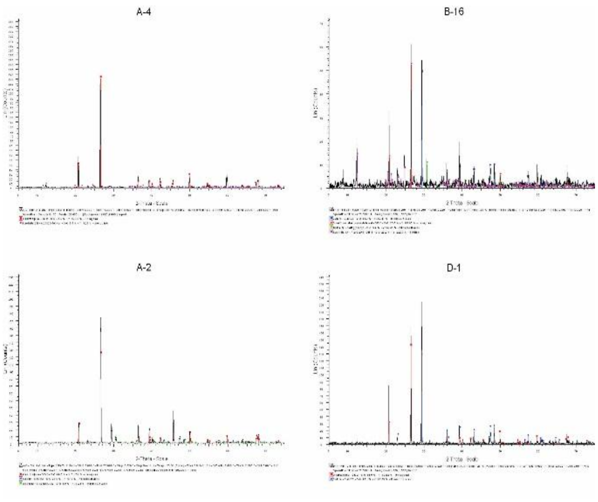

Fig. 15 Selected X-ray Diffractograms of some samples showing the presence of quartz, calcite, dolomite and kaolinite having major peaks at 26.2, 29.5, 30.5 and 12.5 two-theta respectively. The % of minerals is variable but quartz and calcite are dominant constituents.

Most of samples are composed of sedimentary lithics. These are mainly bio-lithics and lithics of mudstone (Fig. 6). The sedimentary lithics are composed of rounded quartz and mud matrix. The percentage of clay matrix is variable, but in one sample it reaches up to 10%. Bioclasts are in variable proportion ranging between 5-20% (Fig. 6). The higher percentage of bioclasts suggests the shallow marine conditions for sediment deposition (Sahito et al., 2013). The bioclasts are abundant in well B, but occur in comparatively lesser amount in well A and D. The classification of sandstones on QFL plot shows that bulk of the samples plot in the field of quartz arenite, followed by sub-litharenite and sub-arkose. However, some of the samples also belong to litharenite and feldspathic litharenite types (Fig. 7; Table 2). Along with diagenesis, the current mineral assemblage of accessory minerals shows a granitic source for the sediments of Goru Formation (Table 3).

Controls on Reservoir Quality

Present results indicate that the lower Goru B sands of early Cretaceous were subjected to intense mechanical compaction and associated diagenetic processes, which resulted in loss of primary porosity. Two generations of calcite cements were identified, whereas silica cementation is also present as quartz overgrowth. The formation of early calcite matrix minimized the primary porosity and prevented further quartz cementation. The calcite cement occurs as complete or partial replacement of detrital components, quartz and feldspar. This cementation penetrated into the grain pores where some of the pores, were filled later by authigenic calcite.

The dissolution of feldspar and other grains during early and late stages of diagenesis gave rise to secondary porosity. The early porosity was partially lost by authigenic cements such as calcite, quartz and clay. Second episode of dissolution took place at greater depths during late stage, resulting in dissolution of authigenic minerals that created secondary porosity. Late diagenetic deformation is evident in the form of undulose extinction and in-situ fractured quartz grains. Late diagenetic pressure dissolution is also evident from sutured contacts and by the presence of minor stylolites,

In the diagenetic sequence, the microcrystalline calcite is of earlier stage, while the coarse sparry calcite indicates late diagenetic events. In most of the thin sections, the corrosion of quartz was observed. The undulose extinction and fracturing of quartz grains indicate that the area remained under tectonic stress resulting in post-depositional fracturing, a product of late diagenesis. The SEM images at 50 micrometer size show irregular type of fracturing within the quartz grains. Late stage fracturing of quartz has also generated various types of channels enhancing the secondary porosity.

Conclusion

The diagenetic processes resulted in the loss of primary porosity in lower Goru B sands of early Cretaceous age in the subsurface of Badin block. The quartz overgrowth and formation of early calcite matrix reduced the primary porosity and prevented further quartz cementation. However, the dissolution of feldspar and other grains during early and late stages of diagenesis gave rise to secondary porosity. Second episode of dissolution took place at greater depth during late stage and resulted in the dissolution of authigenic minerals and the formation of secondary porosity designated as late stage diagenetic events. The QFL plot indicates that most of the samples fall in the field of quartz arenite, sub-litharenite and sub-arkose, respectively. A few of the samples plot in the litharenite and feldspathic litharenite fields. The quartz overgrowth observed in some samples is the product of late stage diagenesis. The micro-crystalline cement in the form of calcite is mostly present within the pores. It is concluded that diagenesis played a vital role in the alteration of B sand unit and enhancing the quality of B sand as reservoir rock by increasing the porosity due to quartz fracturing, feldspar dissolution, alteration and quartz corrosion. Therefore, the observations made on the diagenetic characteristics of B sand in three wells may be appended by incorporating the data of more wells from different fields for better evaluation of its reservoir characteristics at regional, spatial and temporal scales.

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